

# Interacting new agegraphic tachyon, K-essence and dilaton scalar field models of dark energy in non-flat universe

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## Abstract

We study the correspondence between the tachyon, K-essence and dilaton scalar field models with the interacting new agegraphic dark energy model in the non-flat FRW universe. We reconstruct the potentials and the dynamics for these scalar field models, which describe accelerated expansion of the universe.

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# 1 Introduction

Type Ia supernovae observational data suggest that the universe is dominated by two dark components containing dark matter and dark energy [1]. Dark matter (DM), a matter without pressure, is mainly used to explain galactic curves and large-scale structure formation, while dark energy (DE), an exotic energy with negative pressure, is used to explain the present cosmic accelerating expansion. However, the nature of DE is still unknown, and people have proposed some candidates to describe it. The cosmological constant,  $\Lambda$ , is the most obvious theoretical candidate of DE, which has the equation of state  $\omega = -1$ . Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles [2]. Also the "fine-tuning" and the "cosmic coincidence" problems are the two well-known difficulties of the cosmological constant problems [3].

There are different alternative theories for the dynamical DE scenario which have been proposed by people to interpret the accelerating universe. i) The scalar-field models of DE including quintessence [4], phantom (ghost) field [5], K-essence [6] based on earlier work of K-inflation [7], tachyon field [8], dilatonic ghost condensate [9], quintom [10], and so forth. ii) The interacting DE models including Chaplygin gas [11], holographic DE models [12], and braneworld models [13], etc.

Recently, the original agegraphic dark energy (OADE) and new agegraphic dark energy (NADE) models were proposed by Cai [14] and Wei & Cai [15], respectively. Cai [14] proposed the OADE model to explain the accelerated expansion of the universe, based on the uncertainty relation of quantum mechanics as well as the gravitational effect in general relativity. The OADE model had some difficulties. In particular, it cannot justify the matter-dominated era [14]. This motivated Wei and Cai [15] to propose the NADE model, while the time scale is chosen to be the conformal time instead of the age of the universe. The evolution behavior of the NADE is very different from that of the OADE. Instead the evolution behavior of the NADE is similar to that of the holographic DE [12]. But some essential differences exist between them. In particular, the NADE model is free of the drawback concerning causality problem which exists in the holographic DE model. The ADE models assume that the observed DE comes from the spacetime and matter field fluctuations in the universe [15, 16]. The ADE models have been studied in ample detail by [17, 18, 19].

Besides, as usually believed, an early inflation era leads to a flat universe. This is not a necessary consequence if the number of e-foldings is not very large [20]. It is still possible that there is a contribution to the Friedmann equation from the spatial curvature when studying the late universe, though much smaller than other energy components according to observations. Therefore, it is not just of academic interest to study a universe with a spatial curvature marginally allowed by the inflation model as well as observations. Some experimental data have implied that our universe is not a perfectly flat universe and that it possesses a small positive curvature [21].

All mentioned in above motive us to consider the interacting NADE model in the non-flat FRW and investigate its correspondence with the tachyon, K-essence and dilaton scalar field models. To do this, in Section 2, we obtain the equation of state parameter for the NADE model in a non-flat universe. In Section 3, we suggest a correspondence between the NADE and the tachyon, K-essence and dilaton scalar field models in the presence of a spatial curvature. We reconstruct the potentials and the dynamics for these scalar field models, which describe accelerated expansion. Section 4 is devoted to conclusions.

## 2 Interacting NADE model in a non-flat universe

We consider the Friedmann-Robertson-Walker (FRW) metric for the non-flat universe as

$$ds^2 = -dt^2 + a^2(t) \left( \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right), \quad (1)$$

where  $k = 0, 1, -1$  represent a flat, closed and open FRW universe, respectively. Observational evidences support the existence of a closed universe with a small positive curvature ( $\Omega_k \sim 0.02$ ) [21].

For the non-flat FRW universe containing the DE and DM, the first Friedmann equation has the following form

$$H^2 + \frac{k}{a^2} = \frac{1}{3M_p^2} (\rho_\Lambda + \rho_m), \quad (2)$$

where  $\rho_\Lambda$  and  $\rho_m$  are the energy density of DE and DM, respectively. Let us define the dimensionless energy densities as

$$\Omega_m = \frac{\rho_m}{\rho_{cr}} = \frac{\rho_m}{3M_p^2 H^2}, \quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} = \frac{\rho_\Lambda}{3M_p^2 H^2}, \quad \Omega_k = \frac{k}{a^2 H^2}, \quad (3)$$

then, the first Friedmann equation yields

$$\Omega_m + \Omega_\Lambda = 1 + \Omega_k. \quad (4)$$

Following [18], the energy density of the NADE is given by

$$\rho_\Lambda = \frac{3n^2 M_p^2}{\eta^2}, \quad (5)$$

where the numerical factor  $3n^2$  is introduced to parameterize some uncertainties, such as the species of quantum fields in the universe, the effect of curved spacetime (since the energy density is derived for Minkowski spacetime), and so on. The astronomical data for the NADE gives the best-fit value (with  $1\sigma$  uncertainty)  $n = 2.716_{-0.109}^{+0.111}$  [19]. Also  $\eta$  is conformal time of the FRW universe, and given by

$$\eta = \int \frac{dt}{a} = \int_0^a \frac{da}{Ha^2}. \quad (6)$$

From definition  $\rho_\Lambda = 3M_p^2 H^2 \Omega_\Lambda$ , we get

$$\eta = \frac{n}{H\sqrt{\Omega_\Lambda}}. \quad (7)$$

We consider a universe containing an interacting NADE density  $\rho_\Lambda$  and the cold dark matter (CDM), with  $\omega_m = 0$ . The energy equations for NADE and CDM are

$$\dot{\rho}_\Lambda + 3H(1 + \omega_\Lambda)\rho_\Lambda = -Q, \quad (8)$$

$$\dot{\rho}_m + 3H\rho_m = Q, \quad (9)$$

where following [22], we choose  $Q = \Gamma\rho_\Lambda$  as an interaction term and  $\Gamma = 3b^2 H(\frac{1+\Omega_k}{\Omega_\Lambda})$  is the decay rate of the NADE component into CDM with a coupling constant  $b^2$ . Although this expression for the interaction term may look purely phenomenological but different Lagrangians have been proposed in support of it [23]. The choice of the interaction between both components was to

get a scaling solution to the coincidence problem such that the universe approaches a stationary stage in which the ratio of DE and DM becomes a constant [24]. Note that choosing the  $H$  in the  $Q$ -term is motivated purely by mathematical simplicity. Because from the continuity equations, the interaction term should be proportional to a quantity with units of inverse of time. For the latter the obvious choice is the Hubble factor  $H$ . The dynamics of interacting DE models with different  $Q$ -classes have been studied in ample detail by [25]. It should be emphasized that this phenomenological description has proven viable when contrasted with observations, i.e., SNIa, CMB, large scale structure,  $H(z)$ , and age constraints [26], and recently in galaxy clusters [27].

Taking the time derivative of Eq. (5), using  $\dot{\eta} = 1/a$  and Eq. (7) yields

$$\dot{\rho}_\Lambda = -\frac{2H\sqrt{\Omega_\Lambda}}{na}\rho_\Lambda. \quad (10)$$

Substituting Eq. (10) in (8), gives the equation of state (EoS) parameter of the interacting NADE model as

$$\omega_\Lambda = -1 + \frac{2\sqrt{\Omega_\Lambda}}{3na} - b^2\left(\frac{1 + \Omega_k}{\Omega_\Lambda}\right). \quad (11)$$

### 3 Correspondence between the interacting NADE and scalar field models of DE

Here we suggest a correspondence between the interacting NADE model with the tachyon, K-essence and dilaton scalar field models in the non-flat universe. To establish this correspondence, we compare the interacting NADE density (5) with the corresponding scalar field model density and also equate the equations of state for this models with the EoS parameter given by (11).

#### 3.1 New agegraphic tachyon model

The tachyon field was proposed as a source of the dark energy. The tachyon is an unstable field which has become important in string theory through its role in the Dirac-Born-Infeld (DBI) action which is used to describe the D-brane action [8]. The effective Lagrangian density of tachyon matter is given by [8]

$$\mathcal{L} = -V(\phi)\sqrt{1 + \partial_\mu\phi\partial^\mu\phi}. \quad (12)$$

The energy density and pressure for the tachyon field are as following [8]

$$\rho_T = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \quad (13)$$

$$p_T = -V(\phi)\sqrt{1 - \dot{\phi}^2}, \quad (14)$$

where  $V(\phi)$  is the tachyon potential. The EoS parameter for the tachyon scalar field is obtained as

$$\omega_T = \frac{p_T}{\rho_T} = \dot{\phi}^2 - 1. \quad (15)$$

If we establish the correspondence between the NADE and tachyon DE, then using Eqs. (11) and (15) we have

$$\omega_\Lambda = -1 + \frac{2\sqrt{\Omega_\Lambda}}{3na} - b^2\left(\frac{1 + \Omega_k}{\Omega_\Lambda}\right) = \dot{\phi}^2 - 1, \quad (16)$$

also comparing Eqs. (5) and (13) one can write

$$\rho_\Lambda = \frac{3n^2 M_p^2}{\eta^2} = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}. \quad (17)$$

From Eqs. (16) and (17), one can obtain the kinetic energy term and the tachyon potential energy as follows

$$\dot{\phi}^2 = \frac{2\sqrt{\Omega_\Lambda}}{3na} - b^2 \left( \frac{1 + \Omega_k}{\Omega_\Lambda} \right), \quad (18)$$

$$V(\phi) = 3M_p^2 H^2 \Omega_\Lambda \sqrt{1 - \frac{2\sqrt{\Omega_\Lambda}}{3na} + b^2 \left( \frac{1 + \Omega_k}{\Omega_\Lambda} \right)}. \quad (19)$$

From (18), we obtain the evolutionary form of the tachyon scalar field as

$$\phi(a) - \phi(1) = \int_1^a \frac{da}{Ha} \sqrt{\frac{2\sqrt{\Omega_\Lambda}}{3na} - b^2 \left( \frac{1 + \Omega_k}{\Omega_\Lambda} \right)}, \quad (20)$$

where we take  $a_0 = 1$  for the present time. The above integral cannot be taken analytically. But for the late-time universe, i.e.  $\Omega_\Lambda = 1$ ,  $\Omega_k = 0$  and  $b = 0$ , Eq. (20) reduces to

$$\phi(a) - \phi(1) = \int_1^a \frac{da}{Ha} \sqrt{\frac{2}{3na}}, \quad (21)$$

and the Hubble parameter from Eqs. (2) and (10) can be obtained as

$$H = H_0 \exp \left[ \frac{1}{n} \left( \frac{1}{a} - 1 \right) \right], \quad (22)$$

where  $H_0$  is the Hubble parameter at the present time. Finally, using Eqs. (21) and (22) one can get

$$\phi(a) - \phi(1) = \frac{2e^{1/n}}{H_0} \sqrt{\frac{2\pi}{3}} \left[ \operatorname{erf} \left( \frac{1}{\sqrt{n}} \right) - \operatorname{erf} \left( \frac{1}{\sqrt{na}} \right) \right], \quad (23)$$

where  $\operatorname{erf}(x)$  is the error function defined as

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt. \quad (24)$$

### 3.2 New agegraphic K-essence model

The K-essence scalar field model of DE is also used to explain the observed late-time acceleration of the universe. The K-essence is described by a general scalar field action which is a function of  $\phi$  and  $\chi = \dot{\phi}^2/2$ , and is given by [6, 7]

$$S = \int d^4x \sqrt{-g} p(\phi, \chi), \quad (25)$$

where  $p(\phi, \chi)$  corresponds to a pressure density as

$$p(\phi, \chi) = f(\phi)(-\chi + \chi^2), \quad (26)$$

and the energy density of the field  $\phi$  is

$$\rho(\phi, \chi) = f(\phi)(-\chi + 3\chi^2). \quad (27)$$

The EoS parameter for the K-essence scalar field is obtained as

$$\omega_K = \frac{p(\phi, \chi)}{\rho(\phi, \chi)} = \frac{\chi - 1}{3\chi - 1}. \quad (28)$$

Equating Eq. (28) with the new agegraphic EoS parameter (11),  $\omega_K = \omega_\Lambda$ , we find the solution for  $\chi$

$$\chi = \frac{2 - \frac{2\sqrt{\Omega_\Lambda}}{3na} + b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}{4 - \frac{2\sqrt{\Omega_\Lambda}}{na} + 3b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}. \quad (29)$$

Using Eq. (29) and  $\dot{\phi}^2 = 2\chi$ , we obtain the evolutionary form of the K-essence scalar field as

$$\phi(a) - \phi(1) = \int_1^a \frac{da}{Ha} \left( \frac{4 - \frac{4\sqrt{\Omega_\Lambda}}{3na} + 2b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}{4 - \frac{2\sqrt{\Omega_\Lambda}}{na} + 3b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)} \right)^{1/2}. \quad (30)$$

For the late-time universe, i.e.  $\Omega_\Lambda = 1$ , Eq. (30) by the help of Eq. (22) yields

$$\phi(a) - \phi(1) = \frac{e^{1/n}}{H_0} \int_1^a \frac{e^{-1/na}}{a} \sqrt{\frac{1 - 3na}{1 - 2na}} da. \quad (31)$$

Expanding the integrand appeared in Eq. (31) for  $a > 1$ , one can obtain

$$\phi(a) - \phi(1) = \frac{e^{1/n}}{H_0} \left[ \ln a + \frac{11}{12n} \left( \frac{1}{a} - 1 \right) - \frac{131}{576n^2} \left( \frac{1}{a^2} - 1 \right) + \frac{503}{10368n^3} \left( \frac{1}{a^3} - 1 \right) + O\left( \frac{1}{a^4} - 1 \right) \right]. \quad (32)$$

### 3.3 New agegraphic dilaton field

The dilaton scalar field model of DE is obtained from the low-energy limit of string theory. It is described by a general four-dimensional effective low-energy string action. The coefficient of the kinematic term of the dilaton can be negative in the Einstein frame, which means that the dilaton behaves as a phantom-type scalar field. However, in presence of higher-order derivative terms for the dilaton field  $\phi$  the stability of the system is satisfied even when the coefficient of  $\dot{\phi}^2$  is negative [9]. The pressure (Lagrangian) density and the energy density of the dilaton DE model is given by [9]

$$p_D = -\chi + ce^{\lambda\phi}\chi^2, \quad (33)$$

$$\rho_D = -\chi + 3ce^{\lambda\phi}\chi^2, \quad (34)$$

where  $c$  and  $\lambda$  are positive constants and  $\chi = \dot{\phi}^2/2$ . The EoS parameter for the dilaton scalar field is given by

$$\omega_D = \frac{p_D}{\rho_D} = \frac{-1 + ce^{\lambda\phi}\chi}{-1 + 3ce^{\lambda\phi}\chi}. \quad (35)$$

Equating Eq. (35) with the new agegraphic EoS parameter (11),  $\omega_D = \omega_\Lambda$ , we find the following solution

$$ce^{\lambda\phi}\chi = \frac{2 - \frac{2\sqrt{\Omega_\Lambda}}{3na} + b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}{4 - \frac{2\sqrt{\Omega_\Lambda}}{na} + 3b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}, \quad (36)$$

then using  $\chi = \dot{\phi}^2/2$ , we obtain

$$e^{\frac{\lambda\phi}{2}} \dot{\phi} = \left( \frac{4 - \frac{4\sqrt{\Omega_\Lambda}}{3na} + 2b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)}{c\left(4 - \frac{2\sqrt{\Omega_\Lambda}}{na} + 3b^2\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)\right)} \right)^{1/2}. \quad (37)$$

Integrating with respect to  $a$  we get

$$e^{\frac{\lambda\phi(a)}{2}} = e^{\frac{\lambda\phi(1)}{2}} + \frac{\lambda}{2\sqrt{c}} \int_1^a \frac{da}{Ha} \left( \frac{4na\Omega_\Lambda - \frac{4}{3}\Omega_\Lambda^{\frac{3}{2}} + 2nab^2(1 + \Omega_k)}{4na\Omega_\Lambda - 2\Omega_\Lambda^{\frac{3}{2}} + 3nab^2(1 + \Omega_k)} \right)^{1/2}. \quad (38)$$

For the late-time universe, Eq. (38) by the help of Eq. (22) yields

$$e^{\frac{\lambda\phi(a)}{2}} = e^{\frac{\lambda\phi(1)}{2}} + \frac{\lambda e^{1/n}}{2H_0\sqrt{c}} \int_1^a \frac{e^{-1/na}}{a} \sqrt{\frac{1-3na}{1-2na}} da. \quad (39)$$

Expanding the integrand appeared in Eq. (39) for  $a > 1$ , one can obtain

$$\begin{aligned} \phi(a) = \frac{2}{\lambda} \ln \left[ e^{\frac{\lambda\phi(1)}{2}} + \frac{\lambda e^{1/n}}{2H_0\sqrt{c}} \left[ \ln a + \frac{11}{12n} \left( \frac{1}{a} - 1 \right) - \frac{131}{576n^2} \left( \frac{1}{a^2} - 1 \right) \right. \right. \\ \left. \left. + \frac{503}{10368n^3} \left( \frac{1}{a^3} - 1 \right) + O\left( \frac{1}{a^4} - 1 \right) \right] \right]. \end{aligned} \quad (40)$$

## 4 Conclusions

Here we considered the interacting NADE model with CDM in the non-flat FRW universe. We established a correspondence between the NADE density with the tachyon, K-essence and dilaton energy density in the non-flat FRW universe. We reconstructed the potentials and the dynamics of these scalar field models which describe tachyon, K-essence and dilaton cosmology.

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